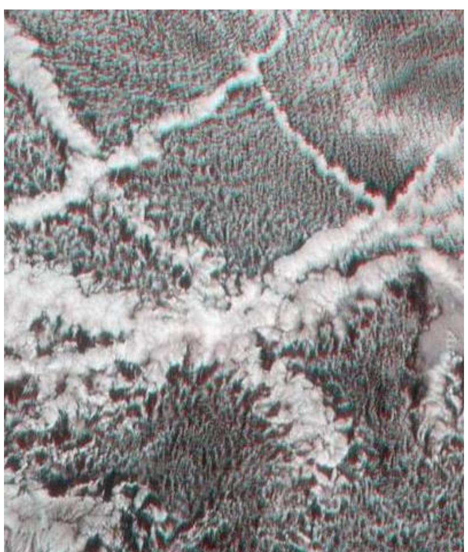
Aerosol indirect effect using a fast and accurate global aerosol microphysics model

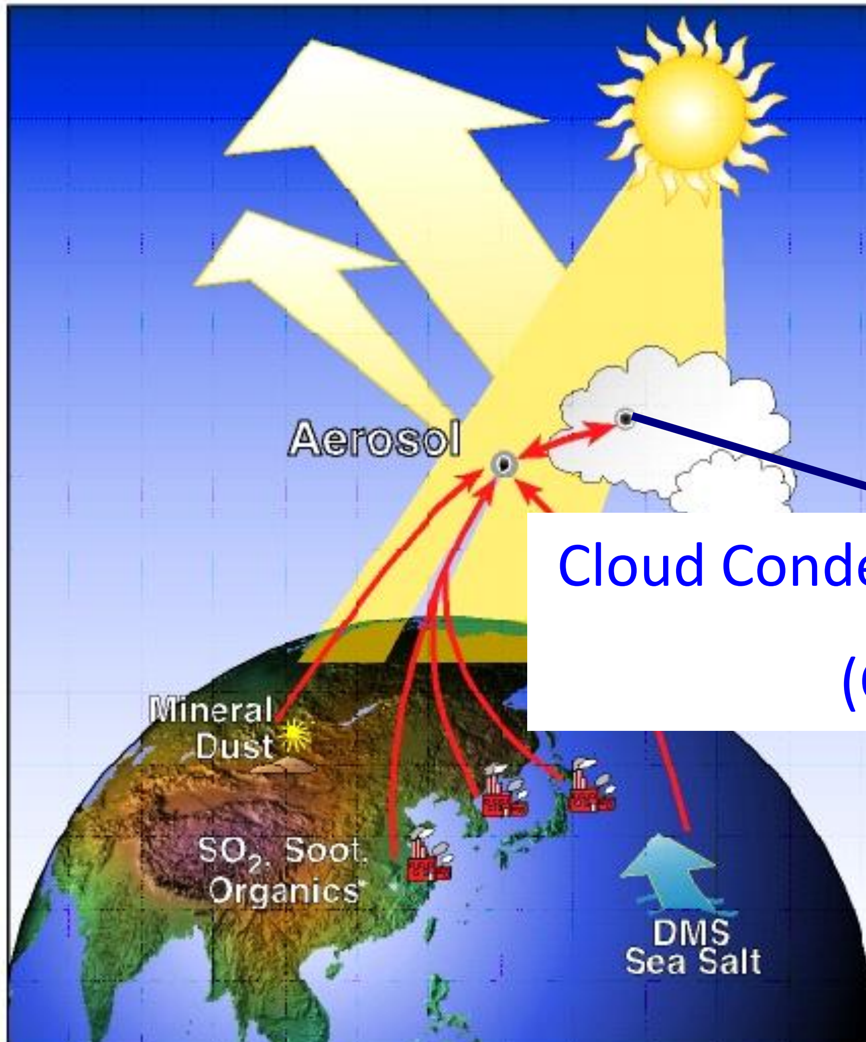
1) Impacts of nucleation chemistry on cloud microphysical properties and cloud albedo forcing

2) Impacts of black carbon mitigation on aerosol indirect forcing

Yunha Lee
NASA GISS lunch seminar

Effect of particles on climate



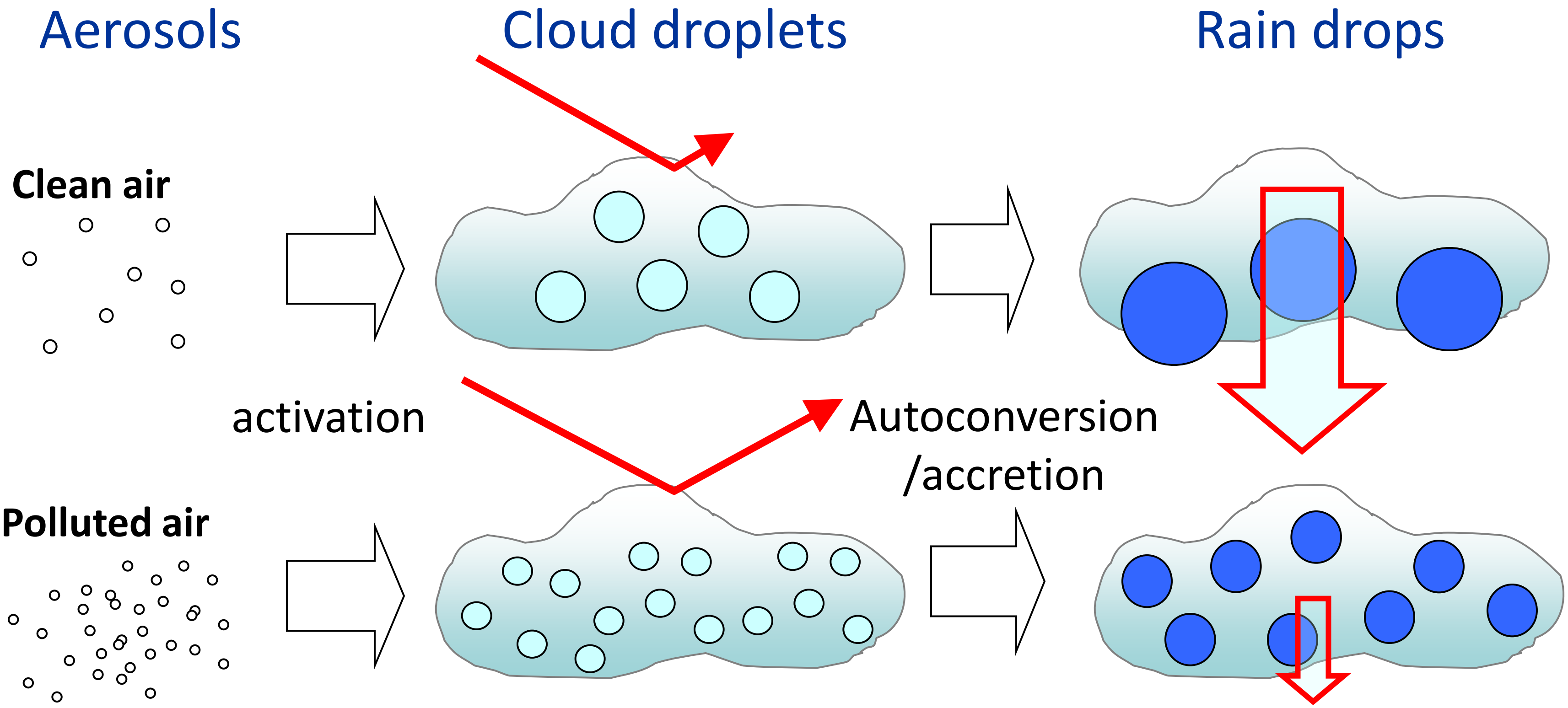


ACE-ASIA overhead 1, 5/20/97 NOAA/PMEL

Cloud Condensation Nuclei

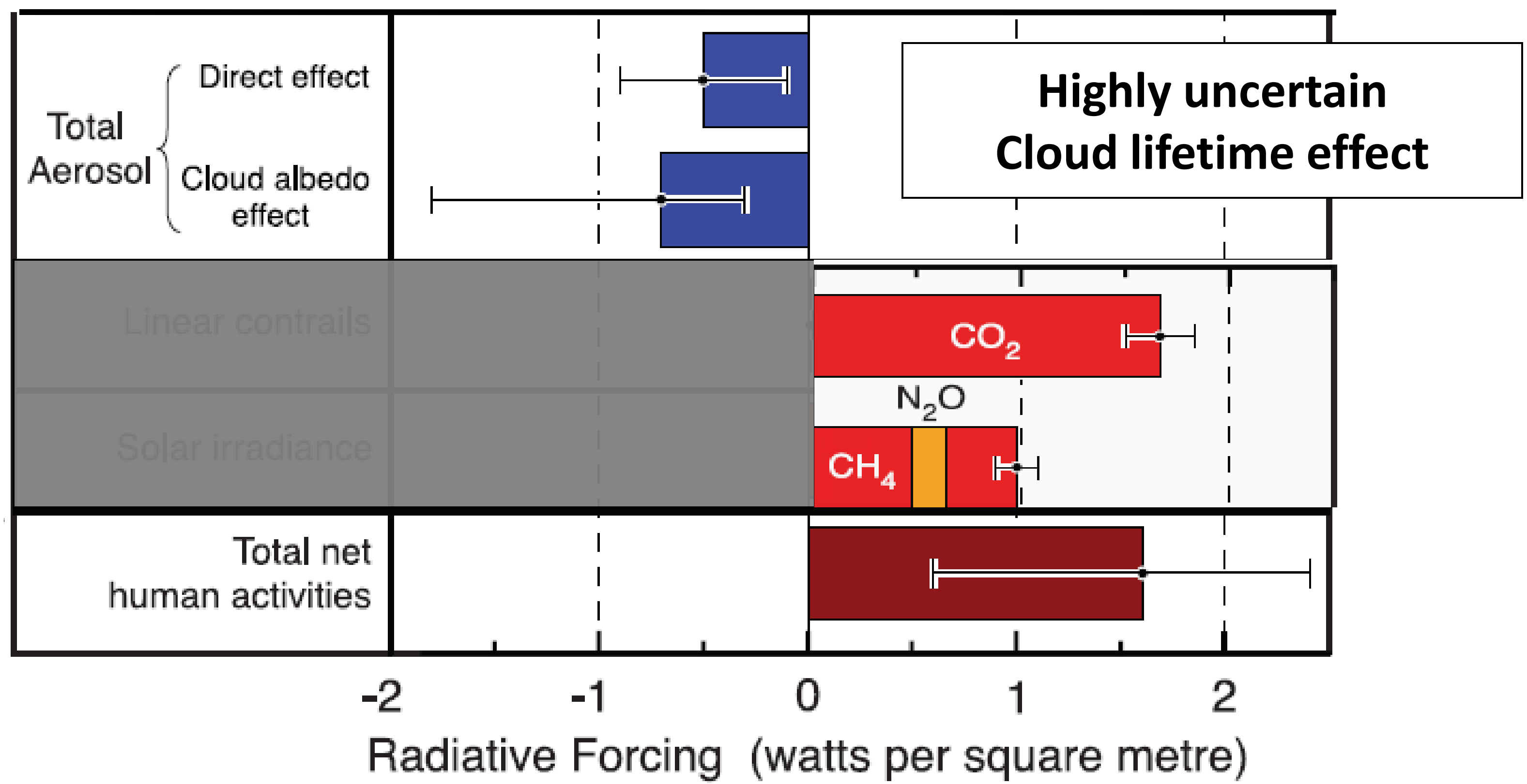
(CCN)

Aerosol indirect effects on Climate

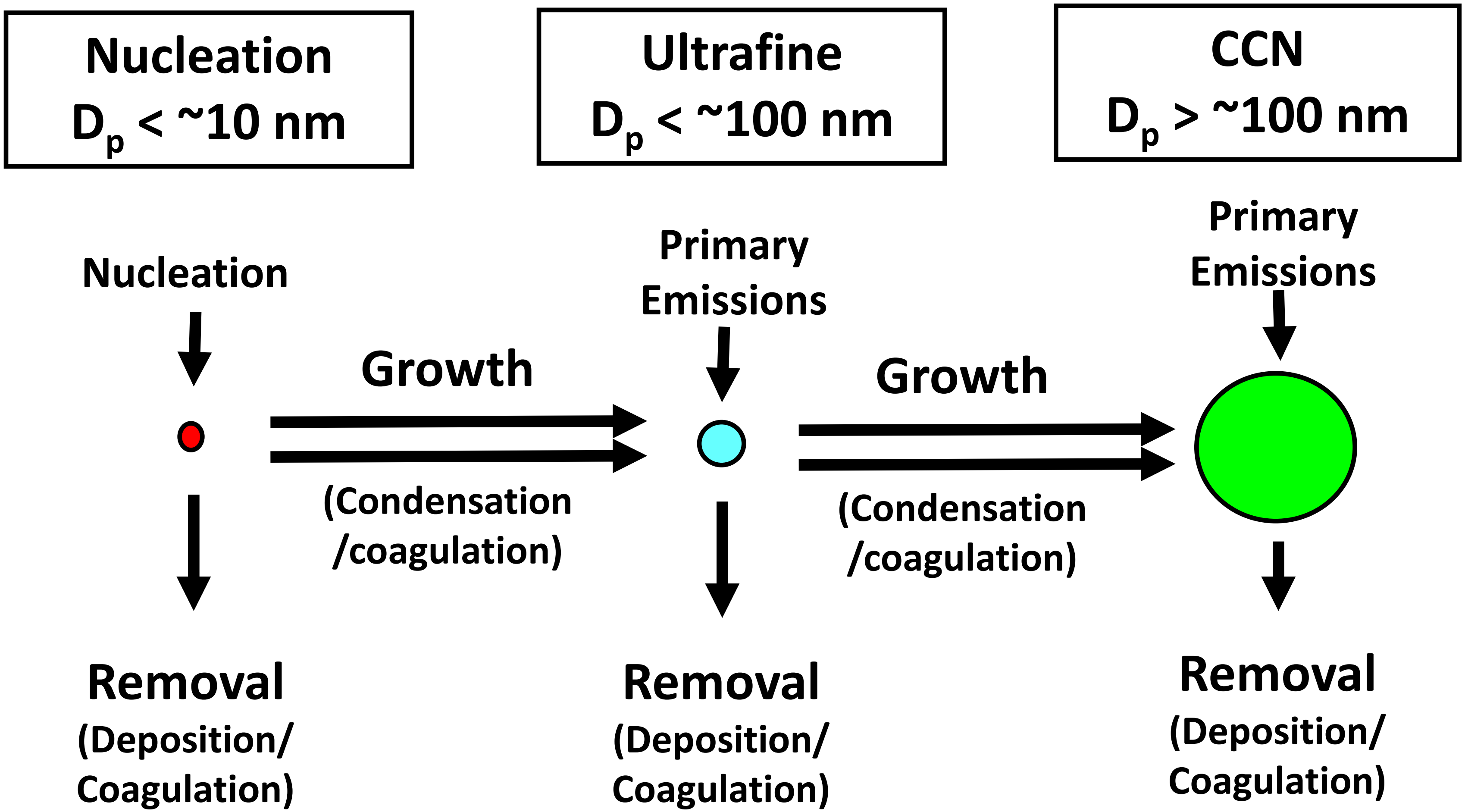


- Brighter cloud = **Cloud albedo effect** (=1st indirect effect)
- Precipitation change = **Cloud lifetime effect** (=2nd indirect effect)

Intergovernmental Panel on Climate Change (IPCC)



Aerosol dynamics



Outlines

3) Fast Global Aerosol Model / Climate Model

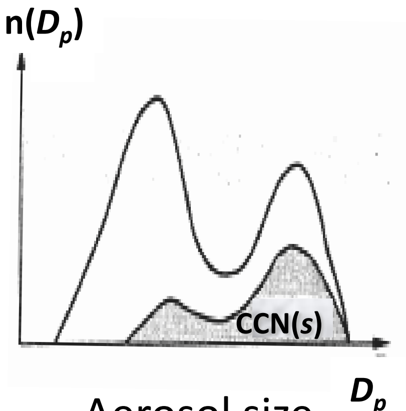
Emissions

- **6) Soot**
- Organic carbon
- Sulfate
- Sea-salt
- **1) Dust**

5) Nucleation

- Binary
- Ternary

Aerosol Microphysics



Aerosol size distribution

4)Nucleation mode dynamics

Cloud albedo

1 year simulation takes more than 2 months computing time

(Comprehensive but “slow”)

rate

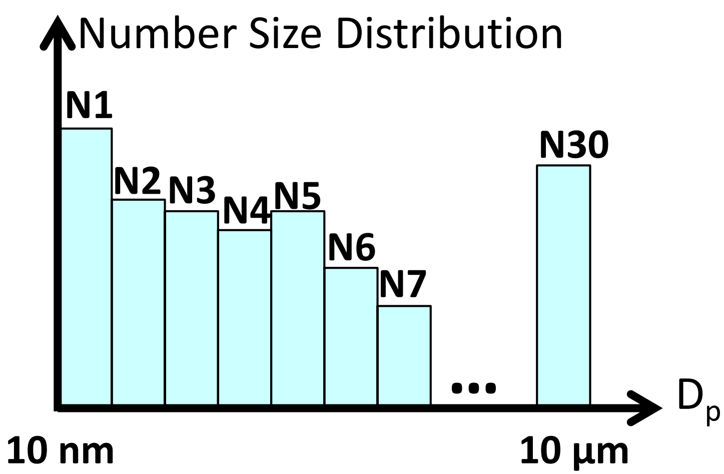
Model applications

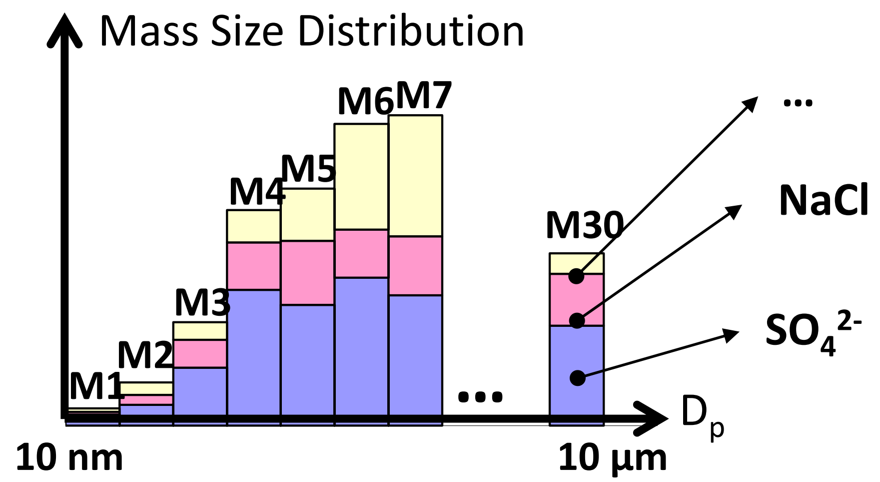
5) Impacts of nucleation chemistry on cloud microphysical properties and aerosol indirect forcing

6) Impacts of black carbon mitigation on aerosol indirect forcing

Global Aerosol Microphysics Model

- Host model: Goddard Institute for Space Studies General Circulation Model II' (GISS GCM II')
- Aerosol species: Sulfate, Sea-salt, Carbonaceous, Mineral dust
- TwO-Moment Aerosol Sectional (TOMAS) algorithm
  - Moments: 1) number and 2) mass
  - 30 bins segregated by dry mass per particle
- Processes: Condensation, Coagulation, Nucleation, Cloud processing



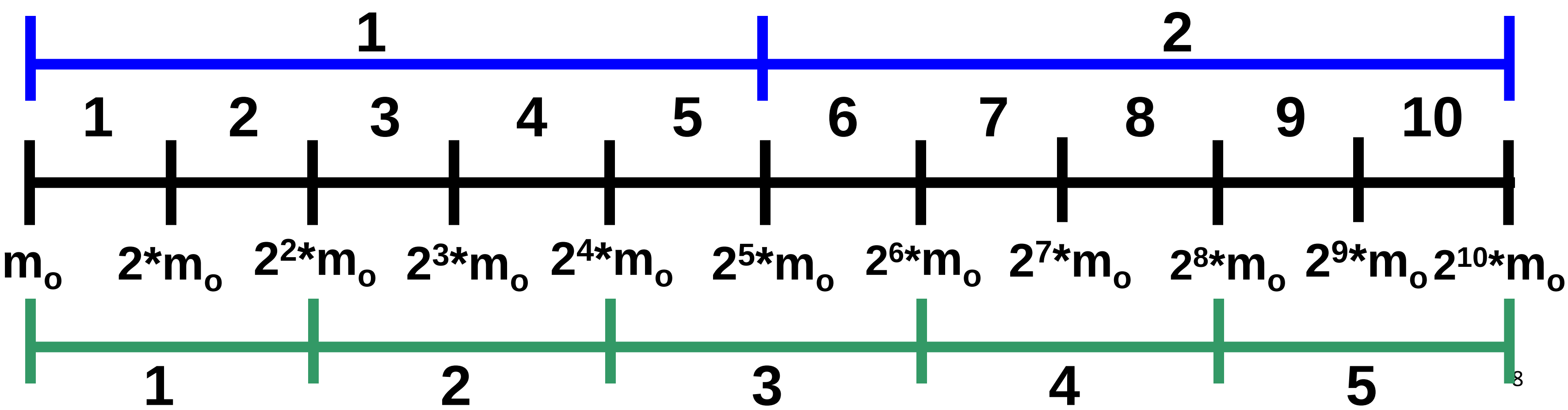


TOMAS 30/15/12 configurations

Reducing size resolution

TOMAS-30	10 bins	10 bins	10 bins
TOMAS-15	5 bins	5 bins	5 bins
TOMAS-12	5 bins	5 bins	2 bins

0.01 μm 0.1 μm 1 μm 10 μm

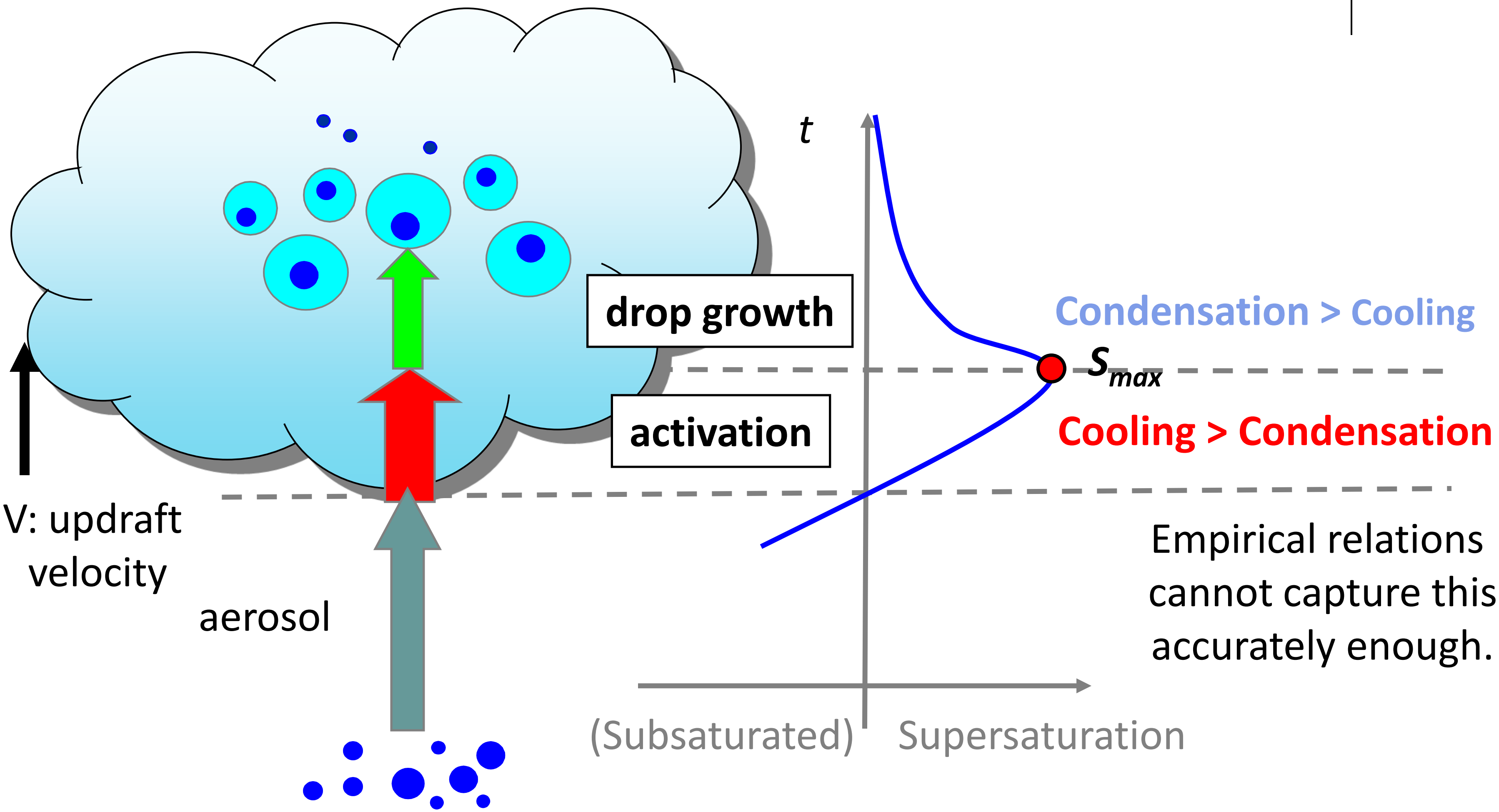


Computing time

Number of size bins	Simulation time for a year*
TOMAS-30	**60 days**
TOMAS-15	**26 days**
TOMAS-12	**18.5 days**

* Based on a single processor in
SGI ORIGIN 2000

Cloud formation and activation



Empirical relations cannot capture this accurately enough.

Modified slide obtained from Athanasios Nenes

Activation parameterization : "Population Splitting"

(Obtained from Dr. Nenes in Georgia Tech)

How: Solve the algebraic equation for S_{max} (numerically)

Input: P,T, updraft velocity (cooling rate), RH, aerosol characteristics.

Output: Cloud droplet number concentration (CDNC), S_{max}

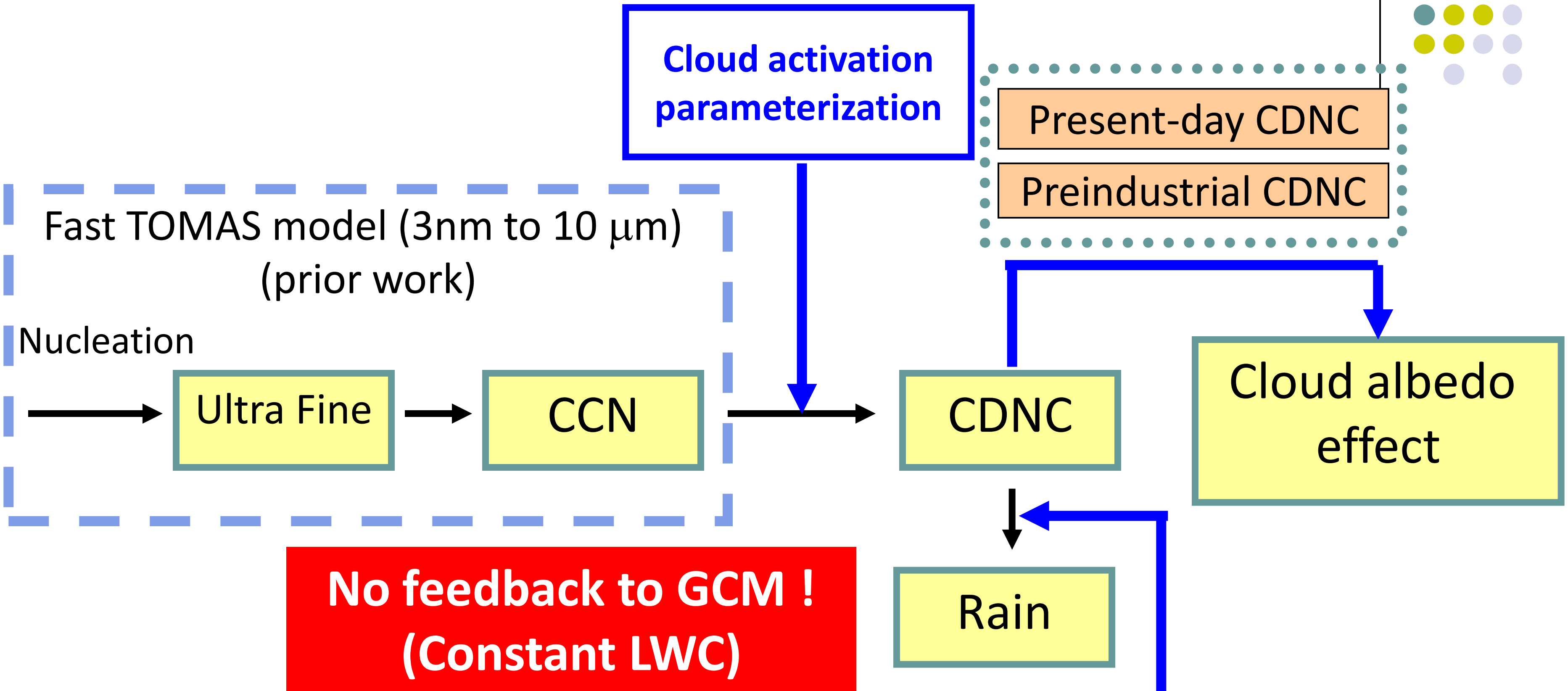
$$\frac{dS}{dt} = \text{Cooling rate} - \text{Water vapor condensation}$$

At S_{max}, $dS/dt = 0$

Cooling rate = Water vapor condensation

Kinetically limited CCN | **Recently activated CCN**

Aerosol-cloud interaction



Four autoconversion parameterizations:

- F(*LWC*, *CDNC*) - **KK** [Khairoutdinov and Kogan, 2000] & **MC** [Manton and Cotton, 1977]
- F(*LWC*, *CDNC*, *dispersion*) – **BH** [Beheng, 1994] & **P6** [Liu and Daum, 2004]

Autoconversion parameterizations

Names	Inputs	References	Autoconversion rate [kg m^{-3} s^{-1}]
SD	LWC	Sundqvist [1989]	SD: $CDNC^{0}$
MC	CDNC, LWC	Manton and Cotton [1977]	MC: $CDNC^{-1/3}$
KK	CDNC, LWC	Khairoutdinov and Kogan [2000]	KK: $CDNC^{-1.79}$
P6	CDNC, LWC, dispersion	Liu and Daum [2004]	P6: $CDNC^{-1.0}$
BH	CDNC, LWC, dispersion	Beheng [1994]	BH: $CDNC^{-3.3}$

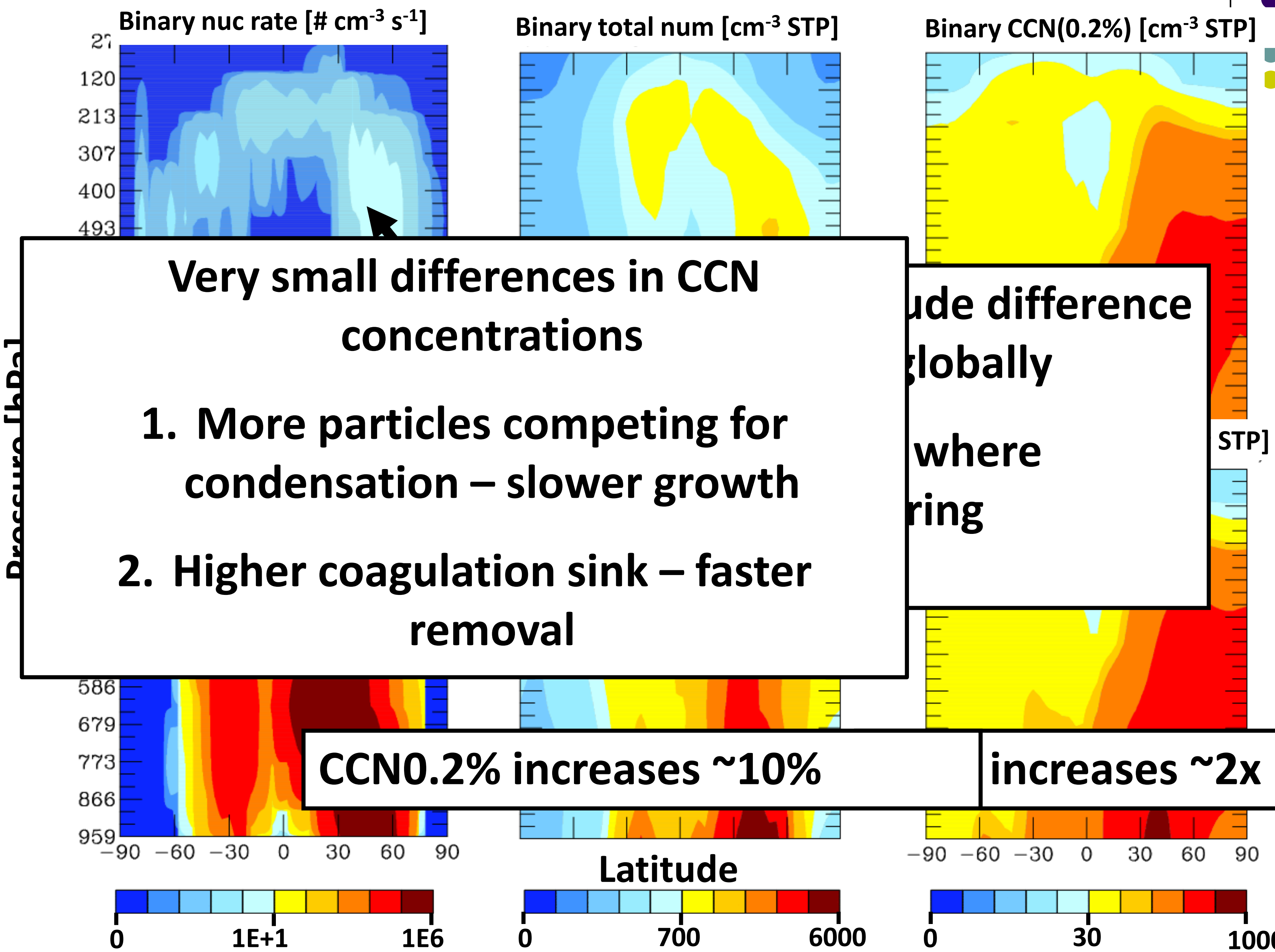
Impacts of nucleation on cloud microphysical properties and aerosol indirect forcing

Model application 1

Nucleation uncertainty

- Several proposed nucleation mechanisms
  - Binary (H_2SO_4-H_2O)
  - Ternary (H_2SO_4-NH_3-H_2O)
  - Ion-induced nucleation (also involves H_2SO_4)
- Nucleation rates vary by orders of magnitude
- How does this nucleation uncertainty affect CDNC and aerosol indirect forcing?

Nucleation and CCN



Very small differences in CCN concentrations

1. More particles competing for condensation – slower growth
2. Higher coagulation sink – faster removal

ude difference
globally

where
ring

CCN0.2% increases ~10%

increases ~2x

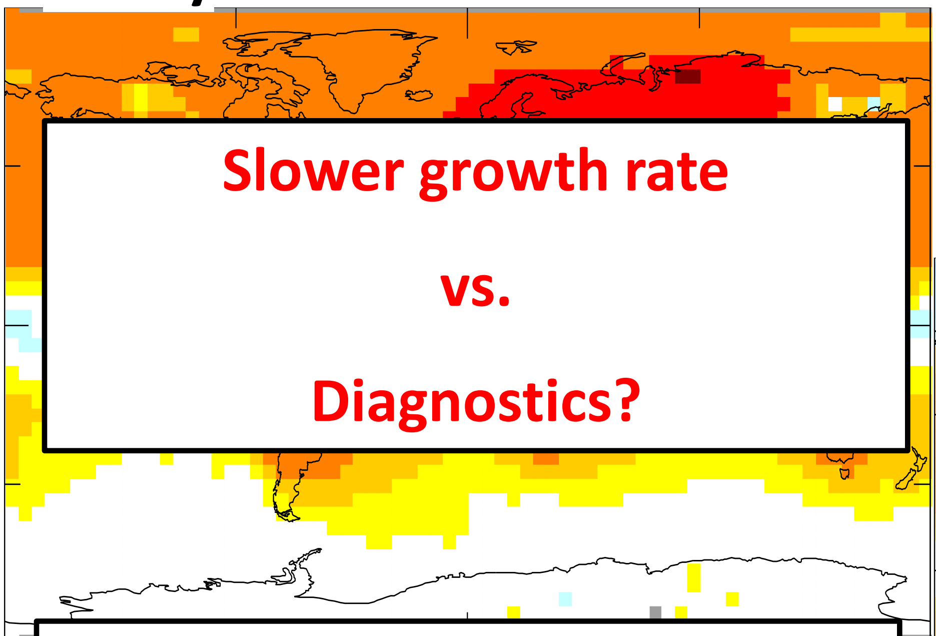
Simulations

Simulations	Emission scenario	Nucleation scheme
BINARY-PD	Present-day	Binary
BINARY-PI	Preindustrial	Binary
TERNARY-PD	Present-day	Ternary
TERNARY-PI	Preindustrial	Ternary

- **Binary** (Vehkamäki et al., 2002): a lower bound of nucleation rate
- **Ternary** (Napari et al., 2002): a upper bound of nucleation rate

First vertical layer CDNC ratio

Binary



Slower growth rate

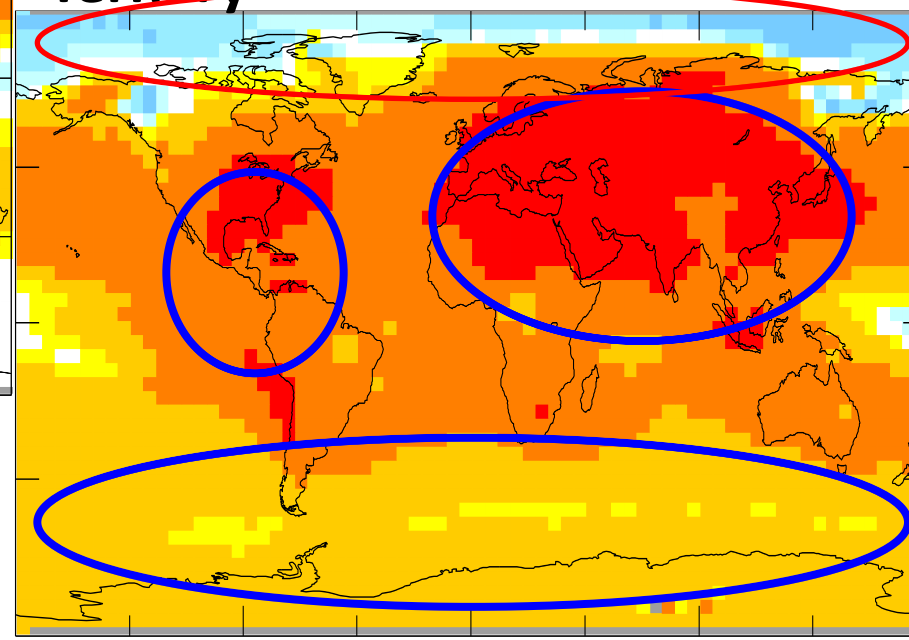
vs.

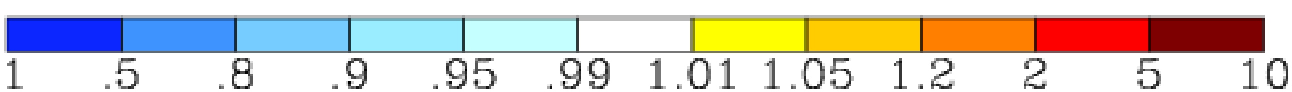
Diagnostics?

With less existing particles, nucleated particles have higher chance to grow.

Present-day / Preindustrial

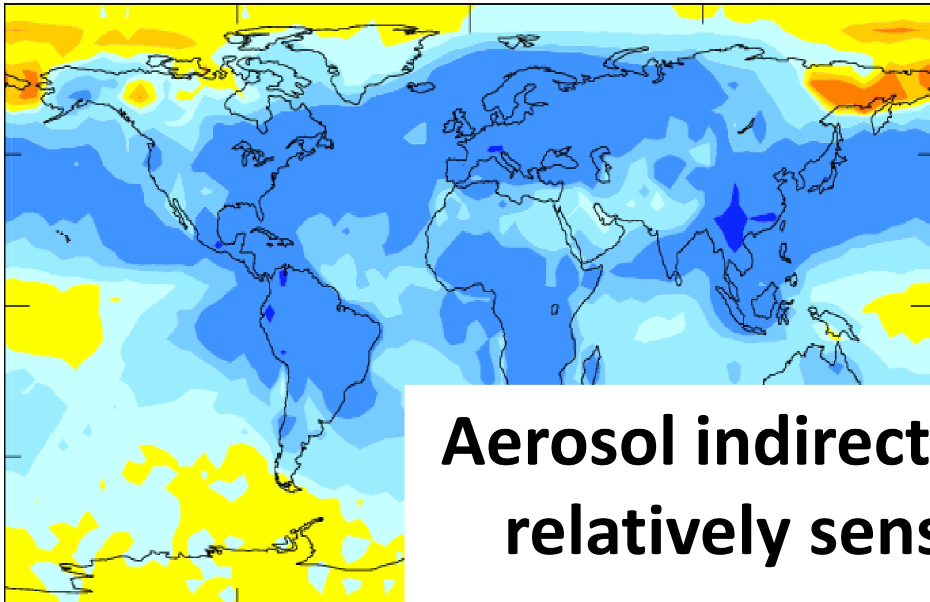
Ternary



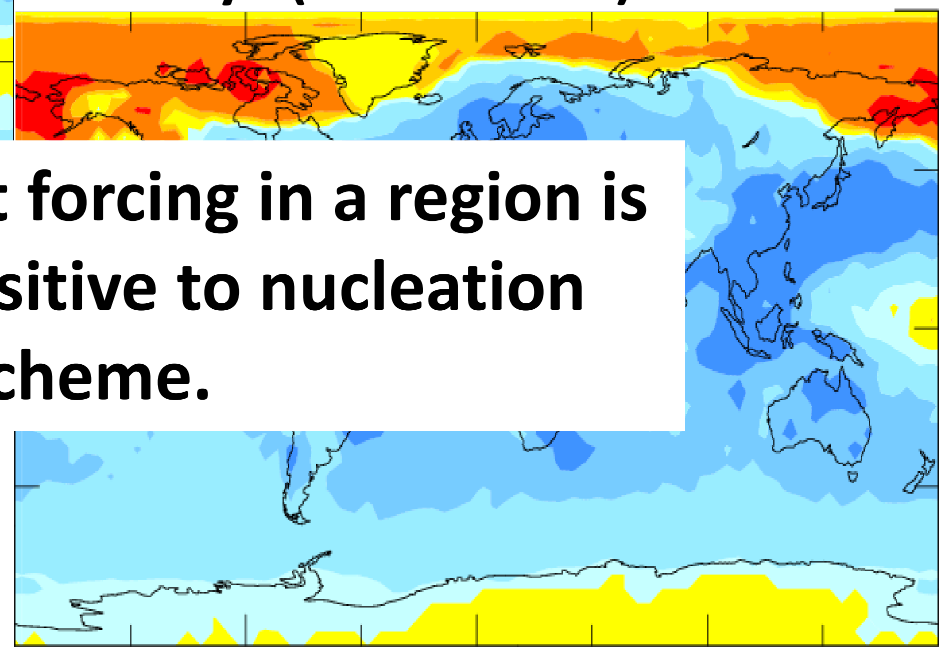


Cloud albedo forcing

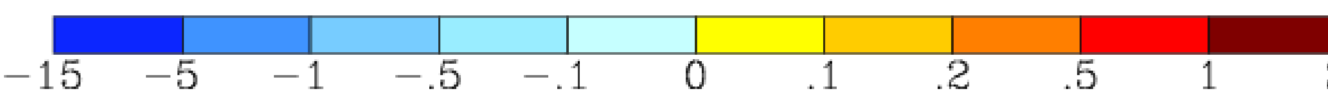
Binary (-0.89 W m^{-2})



Ternary (-0.65 W m^{-2})



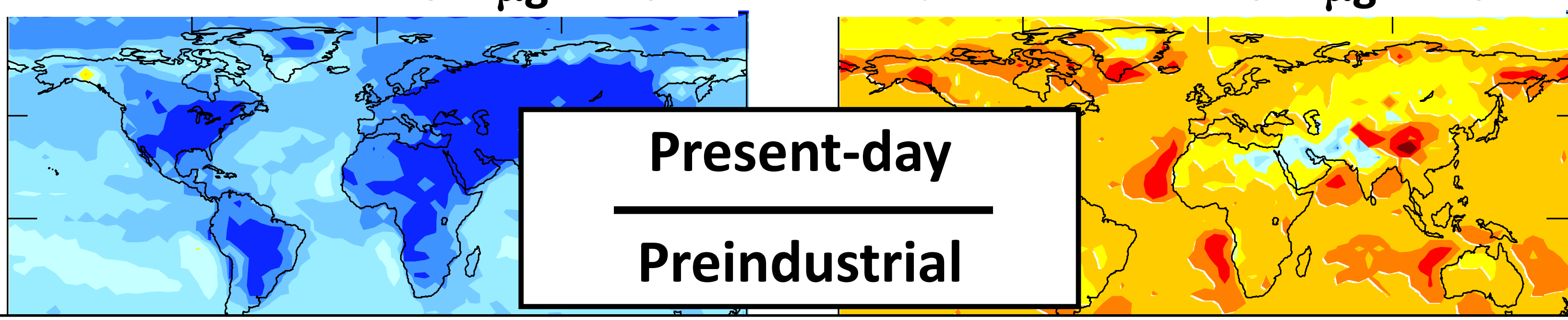
Aerosol indirect forcing in a region is relatively sensitive to nucleation scheme.



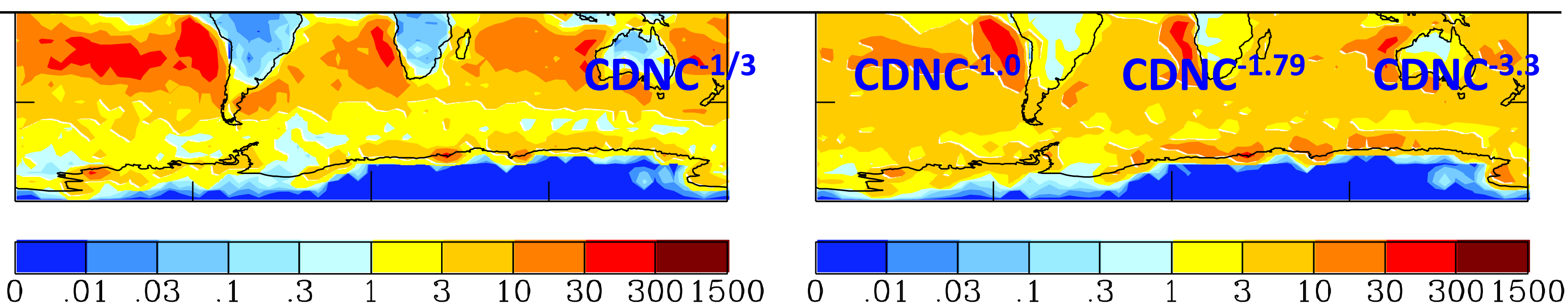
[W m^{-2}]

Autoconversion rate

KK $0.1\ \mu g\ m^{-3}\ s^{-1}$ MC $9.4\ \mu g\ m^{-3}\ s^{-1}$



Simulations	CDNC ratio	MC ratio	P6 ratio	KK ratio	BH ratio
TERNARY	1.6	0.9	0.7	0.7	0.4
BINARY	1.9	0.9	0.7	0.6	0.4



Will black carbon mitigation dampen aerosol indirect forcing?

Policy implication

Collaborators: John Seinfeld/Wei-Ting (Anne) Chen (Caltech); Athanasios Nenes (GaTech)

Publication: W.-T. Chen, Y. H. Lee, P. J. Adams, A. Nenes, and J.H. Seinfeld (2010). Will black carbon mitigation dampen aerosol indirect forcing? *Geophysical Research Letters*

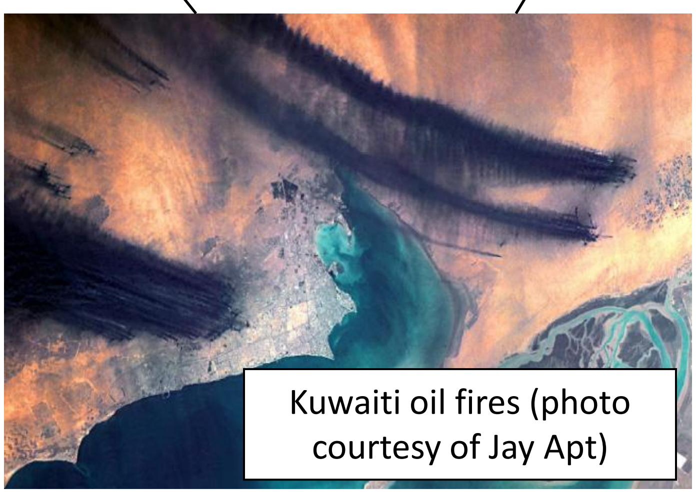
Application: Black Carbon as Climate Mitigation?

Warming

- Sunlight Absorption
- Cloud Burnoff
- Snow/Ice Darkening

Cooling

- Cloud Brightening
- Co-emitted Reflectors



Kuwaiti oil fires (photo courtesy of Jay Apt)

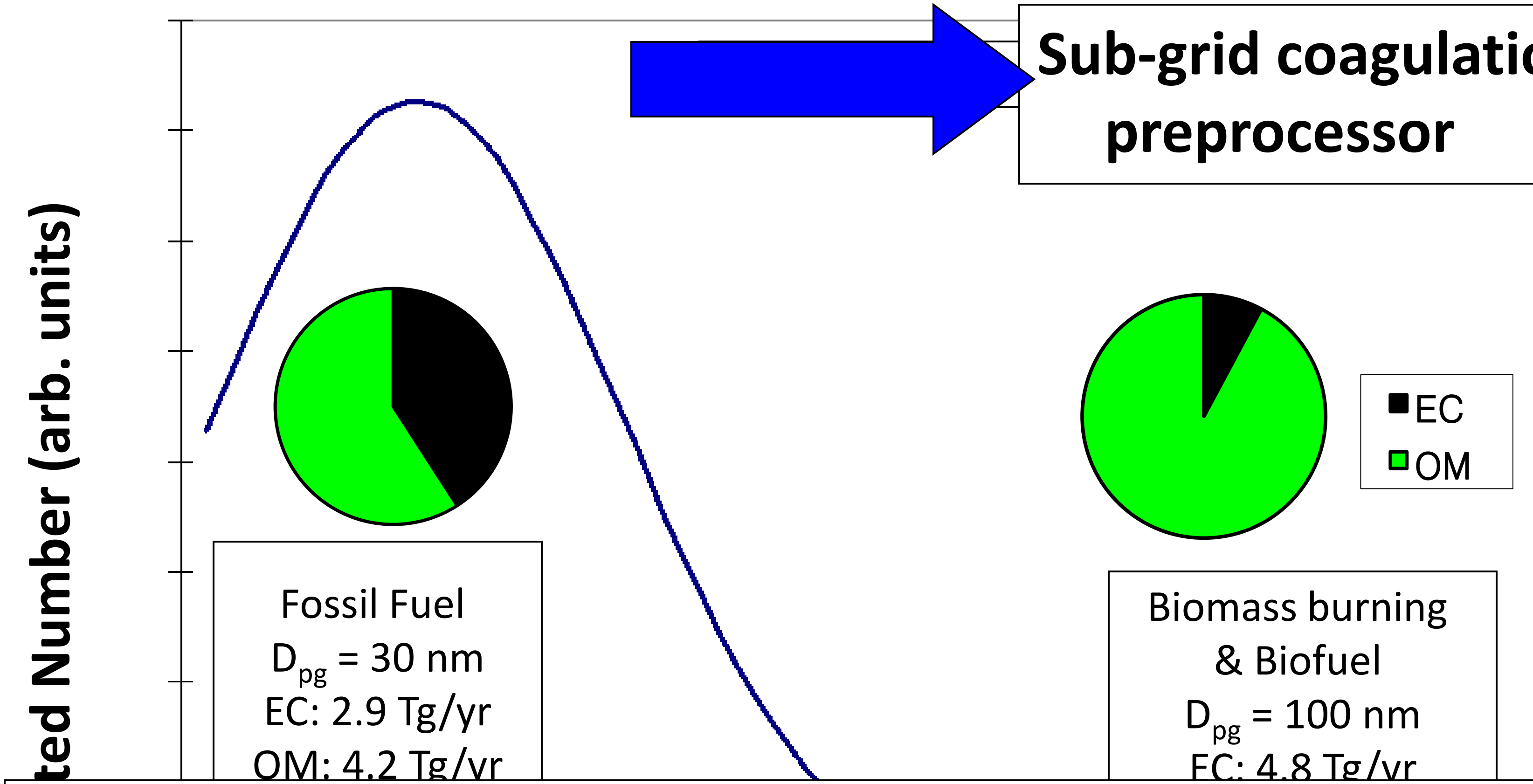
- Black carbon ("soot") controls have been proposed for inclusion in climate change treaties
- (Somewhat) quantified warming effects
- Offsetting cooling effects largely not studied

Black Carbon Reductions

Scenarios:

- **Base case**
- **50% FF: reduce fossil fuel emissions by 50% (EC, OM, Number)**
- **50% CARB: reduce all carbonaceous emissions by 50%**

Sub-grid coagulation preprocessor



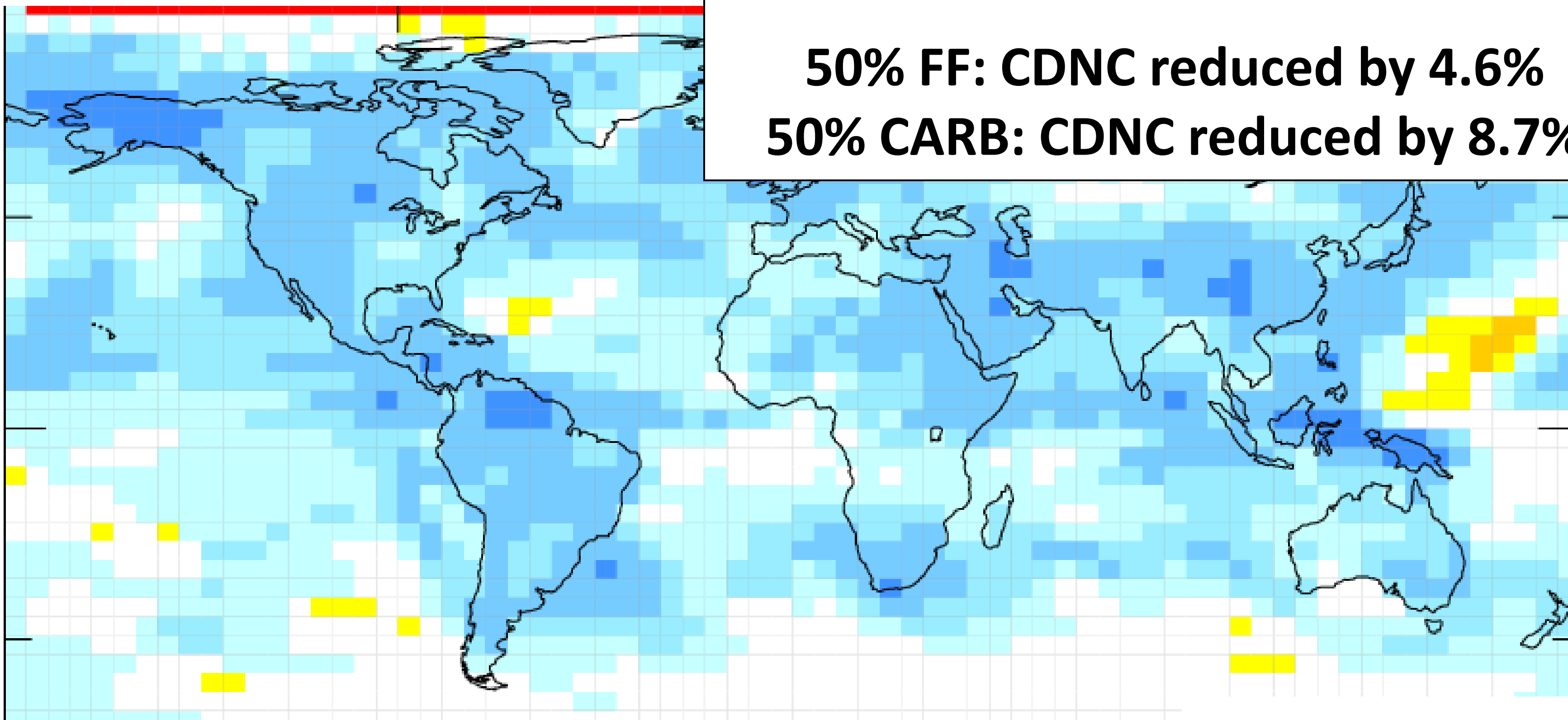
Scenarios:

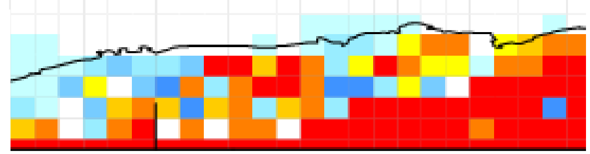
- **Base case**
- **50% FF: reduce fossil fuel emissions by 50% (EC, OM, Number)**
- **50% CARB: reduce all carbonaceous emissions by 50%**

BC Controls Reduce CDNC

In global annual average,

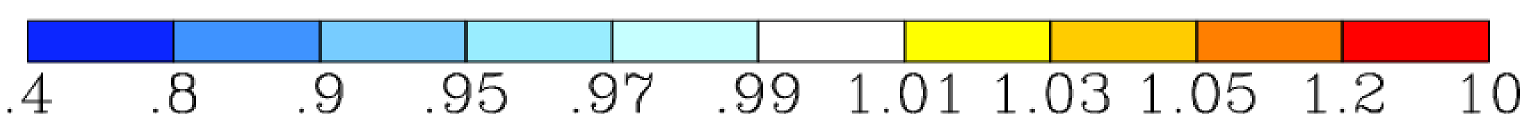
50% FF: CDNC reduced by 4.6%
50% CARB: CDNC reduced by 8.7%



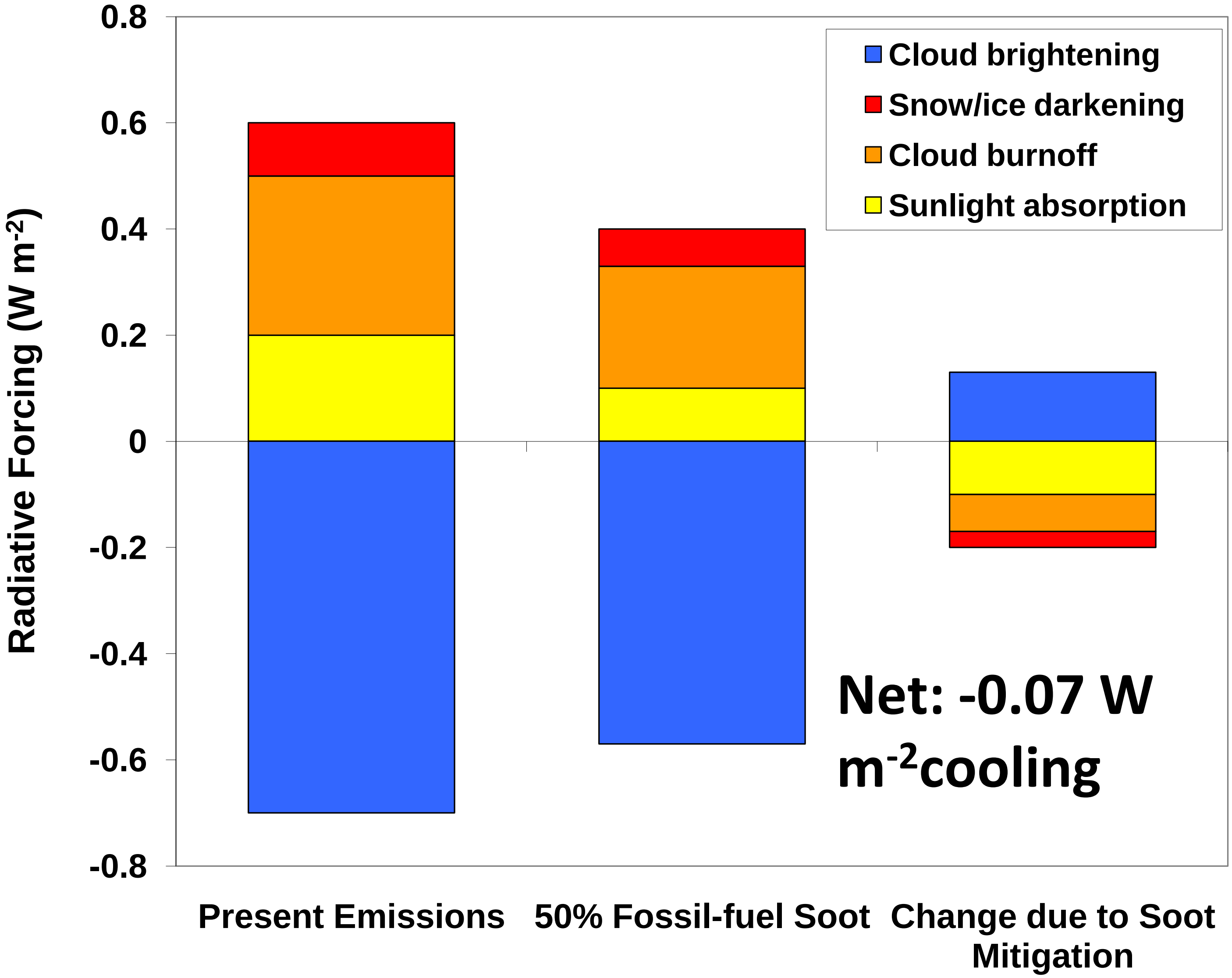


Ratio of cloud droplet number (CDNC)

$$\frac{\text{50\% FF}}{\text{Base case}}$$



Soot Reductions: Forcing Assessment



Conclusions

- The uncertainty in nucleation chemistry to cloud microphysical properties and indirect forcing is assessed.
  - Some regions, CDNC and cloud albedo forcing is sensitive to nucleation scheme.
  - The result is sensitive to how CDNC is calculated (online vs. offline)

- The impact of black carbon mitigation to aerosol indirect forcing is investigated.
  - CCN impacts of reducing black carbon appear to offset a large fraction of climate benefits

Acknowledgement

- Peter J. Adams
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- Athanosis Nenes